Acoustic Noise and Magnetic Resonance Imaging: A Narrative/Descriptive Review

Mark J. McJury, PhD*

Abstract
Magnetic resonance imaging generates unwanted acoustic noise. This review describes the work characterizing the acoustic noise, and the various solutions to control and attenuate the acoustic noise. There are also discussions about the permissible limits, and guidance regarding acoustic noise exposure for staff, patients, and volunteers.
Level of Evidence: 5
Technical Efficacy Stage: 1

J. MAGN. RESON. IMAGING 2022;55:337–346.

Introduction

Most imaging procedures on an MR scanner generate unwanted acoustic noise. At low levels, this can generate annoyance, heightened anxiety in patients, and interfere with communication between staff and patients. At high levels, this becomes a more significant issue. Loud MR acoustic noise can affect successful scan rates, and can also become a safety hazard, requiring control and attenuation measures, to avoid potential hearting damage.[1–9] This hazard is particularly concerning for specific vulnerable patient groups, such as anesthetized patients, those on certain pharmaceutical drugs or with tinnitus, neonates, and pregnant women.[2–4]

The control of MR-related acoustic noise has generated a considerable body of research to characterize the acoustic noise, and a large variety of methods to attenuate and control the acoustic noise levels. Methods include the use of passive ear protection, sequence optimization, antiphase noise, and gradient hardware redesign and retrofitting.

This review (an update of an earlier work[10]) gives a thorough overview covering all aspects of MR-related acoustic noise, permissible limits, and control solutions. Interested readers can find our more detailed and comprehensive review here.[11]

Hearing and Acoustic Noise

Simplistically, we can think of the ear as a wide-band receiver. It can detect sound intensities over a massive range ($\sim 10^{12}$ and over frequencies which vary by a factor of 10^3)—approx. 20 Hz to 20 kHz for normal hearing. In comparison, the eye only detects light frequencies that vary by a factor of 2.

Our hearing involves a mechanical system (which stimulates hairs in the cochlea), sensors that produce action potentials in the auditory nerves, and the auditory cortex (the brain region which decodes signals from the auditory nerves).

The ear is not uniformly sensitive over the hearing range (see Fig. 1)—peak sensitivity is in the range of 2–5 kHz.[12] Sensitivity is also age dependent. Typically, as you age the highest frequency you can hear will decrease, and the sound level needed to hear it will increase. Hearing will also deteriorate more quickly if subjected to continuous loud sounds.

The *loudness* of a sound is a mental response to the physical intensity of the sound. Loudness is approximately proportional to the log of intensity, which compresses the wide range of intensities the ear detects. Loudness also depends strongly on frequency. This log relationship leads to the use of the decibel scale, dB, when dealing with sound

View this article online at wileyonlinelibrary.com. DOI: 10.1002/jmri.27525
Received Nov 11, 2020, Accepted for publication Jan 8, 2021.

*Address reprint requests to: M.J.M., 1345 Govan Road, Glasgow G51 4TF, UK.
Email: mark.mcjury@glasgow.ac.uk
From the Department of Clinical Physics & Bio-Engineering, Level 2, Imaging Centre of Excellence, Queen Elizabeth University Hospital Campus, Glasgow, UK

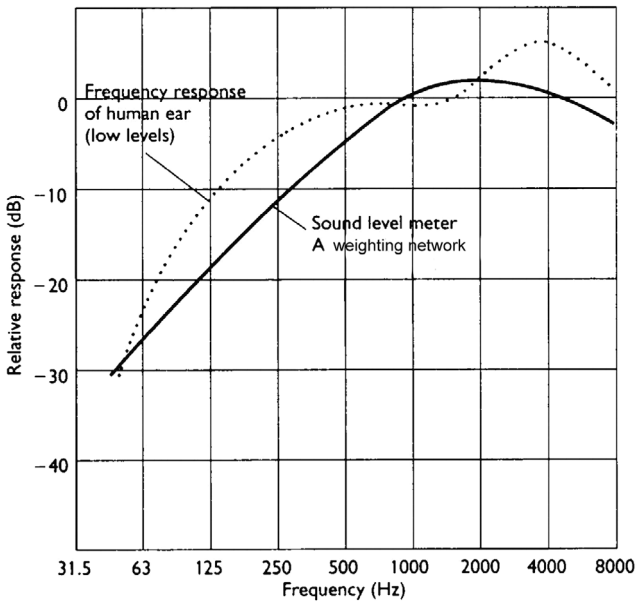

FIGURE 1: The frequency response of the human ear. The dashed line shows the relative frequency response of the human ear and the solid line shows the A-weighted filter approximation to this response.[12] Reproduced by permission through the HMSO Open Government License.

intensity. As there is a frequency dependence to hearing sensitivity, this decibel scale can be filtered to weight readings for the ear's sensitivity. Hence, we often see readings reported in dB(A), and dB(C).

The sound levels measured will also depend not only on the detector used (and weighting) but also on the environment surrounding the sound source and detector. Hence, often sounds levels will be reported as sound pressure level (SPL), which also accounts for the environmental contributions.

Audible noise is often defined as "unwanted" sound. It is characterized by its intensity, frequency range, mode, and duration. Here, by mode, we mean whether the noise is continuous, intermittent, impulsive, or explosive.

Exposure to loud noise can damage hearing. Transient hearing damage can occur, which can result in temporary threshold shift (TTS) in hearing. Hearing recovery is generally exponential and rapid following acoustic noise exposure. Brummett et al reported an early study of patients scanned without ear protection and noted 43% reported experiencing TTSs.[1] If the noise is louder, recovery can take considerably longer, and for severe exposure, permanent threshold shifts (PTS) can occur, resulting in permanent hearing loss for a specific frequency range.

In recent years, there has been increasing interest and growing concern over "hidden hearing loss" (HHL). Damage to the outer hair cells often results in temporary or permanent threshold shifts as mentioned above and can be detected acutely with standard audiological testing. However, damage to the auditory nerve cells and inner hair cells can occur, due, for example, to acoustic noise exposure, but it is not readily detected by standard audiometric testing and can remain hidden for months or years.[13, 14] While not apparent from measurements of hearing thresholds, deficits are found when assessing aspects of hearing (eg, speech discrimination and intelligibility) in the presence of background noise.

Some research has shown that exposure to moderate levels of acoustic noise (~100 dB for ~2 hours) can produce TTS and also result in HHL in animal models.[15] However, at this point, there is much conflicting data, and the characteristics and relationship between HHL and acoustic noise exposure in humans is not clear.

In this review, published data relating to hearing damage are based on standard audiometric testing in humans, but the impact and prevalence of HHL may become increasingly important and may have an impact on future guidance regarding safe levels of acoustic noise exposure in MR.

MRI-Related Acoustic Noise

In the MR environment, the main acoustic noise source is the gradient system. Acoustic noise is generated due to the rapidly changing currents in the gradient coils, and in the presence of large magnetic fields, result in significant Lorentz forces on the coils, which knock against the coil former. Additionally, these forces and gradient designs often result in the gradient former vibrating and deforming, further increasing acoustic noise levels. The various characteristics of the gradient input (wave-form shapes) leads to generation of a wide variety of audible sounds familiar to MR workers and patients.[16]

Scanner Design

Open MR scanners generally have a lower static field strength compared to superconducting scanners. Their open design also minimizes potential acoustic noise amplification due to reverberation found in tunnel-configuration magnetic designs. Hence, open scanners have reported comparatively lower acoustic noise levels[17] and fewer issues with acoustic noise exposures. This review will focus mainly on superconducting MR systems.

Characteristics

The gradient input will alter not only the character of the audible noise but also its loudness. Simplistically, acoustic noise should increase with decreases in slice thickness, field of view (FOV), and echo time (TE).

ACOUSTIC NOISE LEVELS. These are found to be highest for sequences employing multiple gradients simultaneously (eg, three-dimensional acquisitions), and gradients with rapid risetimes (fast imaging) or switching times (echo-planar-type imaging).

Noise levels also show a (nonlinear) dependence on static field strength[18] and in fact (due to effects such as

Lorentz damping) acoustic noise levels for some 7 T whole-body scanners are not significantly higher than those generated by lower field scanners.[19]

FREQUENCY SPECTRUM. Due to the nature of the gradient waveform and associated vibration of gradient formers, the acoustic noise is found to be pseudo-periodic. Periodicity depends mainly on the pulse sequence used and the vibrational characteristics of the gradient coil and former.[20]

Conventional imaging tends to generate peak acoustic noise levels at low frequency, typically in the range of 0.2–1.5 kHz.[21] Unfortunately, this overlaps significantly with the region where hearing is most sensitive and prone to damage.

Echo planar imaging (EPI) sequences are very short in duration. The majority of the acoustic noise generated is from the phase encode "blips," and as these are very short indeed, and the acoustic noise generated contains a higher proportion of high-frequency components.[22]

SPATIAL VARIANCE. Acoustic noise will vary along the scanner bore, depending significantly on scanner design and construction.[17]The acoustic noise may also vary asymmetrically along axial and radial directions due to standing-wave effects.[23]

SYSTEM LOADING. The presence of the patient in the scanner has been reported to cause variations in acoustic noise levels of up to 10 dB.[24]

ULTRA-HIGH FIELD MR. Knowing there is a (nonlinear) dependence between acoustic noise level and static magnetic field strength, we might expect ultra-high field (UHF) scanning to generate considerably higher acoustic noise levels. However, due to effects such as Lorentz damping, this is not seen in practice.[20] Recent studies have reported similar acoustic noise levels measured at 7 T to those at measured at 3 T.[25,26]

Permissible Limits

Scanner acoustic noise levels have been monitored for decades now and often form part of scanner QA and acceptance procedures.

Acoustic noise levels of up to 138 dB[27] have been recorded, and several reports note levels in the range of 120–130 dB ([23, 28]).

The available guidance (depending on your country/region) is similar in nature, being based on chronic exposure, and having similar exposure limits and action levels.

Patients and Volunteers

UK guidance is provided by MHRA,[29] and the relevant action levels are shown in Table 1 (based on reference 30). It suggests offering hearing protection to all, and this should reduce acoustic noise levels at the ear to below 85 dBA.

TABLE 1. Occupational Noise Action Values and Limits (Adapted from reference 30)

Action Level	Daily or Weekly Personal Exposure dB(A) (average value)	Peak Sound Pressure (dB)
Lower exposure value	80	135
Upper exposure value	85	137
Exposure limit values	87	140

Reproduced by permission, HMSO (Open Government License).

Internationally, IEC[31] and ICRIRP[32,33] offer guidance—the latter being based on that from Medicines and Healthcare Regulatory Agency in the United Kingdom.

Staff Exposure

UK guidelines are based on noise at work legislation.[30] Hearing protection should be available for all staff, and wearing is mandatory for acoustic noise levels above the second action level (85 dBA).

In the United States, guidelines are offered by Occupational Safety and Health Authority (OSHA)[34] and American College of Radiology (ACR)[35]; the OSHA guidelines have been adopted by the FDA.[36] OSHA recommend a slightly higher action level of 90 dBA (per day or 8-hour average).

Members of the Public/Carers

Generally, this group will not have access to the MR controlled area, so risks will be low.

Scanning During Pregnancy and Neonatal Imaging

A cautious approach is taken, and imaging during the first trimester of pregnancy is generally avoided except in cases of urgent clinical need.[29] Previous studies have assessed the impact of acoustic noise exposure during pregnancy, but these have mostly focused on chronic occupational noise.

The fetus is known to be sensitive to noise and at risk of hearing damage.[37] Some previous studies have shown that there can be considerable attenuation (around 30 dB) provided by abdominal wall and fluid-filled uterus.[38] However, most of the attenuation will be at higher frequencies; lower frequencies can experience considerably lower attenuation (down to around 5 dB[39]) reducing the sound isolation of the fetus. Indeed, some studies have shown that there can even be enhancement of the low frequencies rather than attenuation, see Fig. 2.[40]

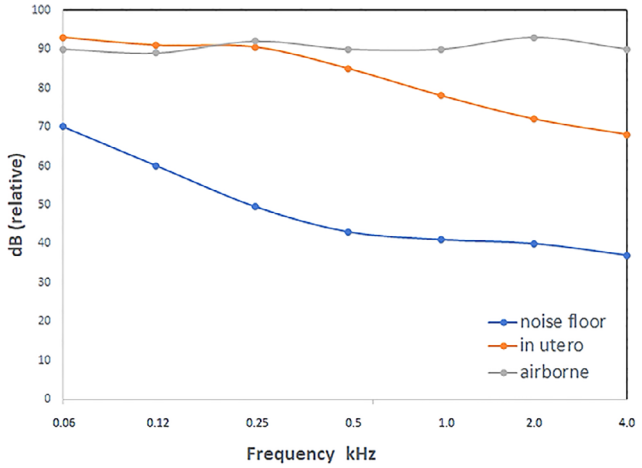

FIGURE 2: Data showing sound transmission to the fetal inner ear. Noise floor refers to maternal physiological background noise. The data are from a model built from existing data on acoustic noise transmission. Reproduced from reference 40.

There have been numerous longitudinal studies which followed up children of mothers scanned during pregnancy. There have been no reports of abnormal hearing or development issues related to MR scanning, including imaging during the first trimester.[41–45]

Neonates are also a group sensitive to acoustic noise. In the United Kingdom, neonatal intensive care unit (NICU) guidelines[46] recommend maintaining acoustic noise levels below 65 dBA to minimize the stress. Solutions for acoustic noise level reduction include the use of dedicated small-bore scanners, with lower strength gradients; the use of dual passive ear protection (ear plugs and muffs); and the use of sound muffling blankets around the neonate in the RF coil.[47, 48]

Acoustic Noise Control Techniques

Passive Protection

Passive ear protection can be thought of as a form of personal protective equipment (PPE). In terms of a solution to unwanted high levels of occupational acoustic noise, the use of PPE is often thought of as a last resort, after solutions involving engineering controls, equipment substitution, and work/task rotation have been exhausted.

However, it also represents the easiest, most convenient, lowest cost and most widely used solution. This protection generally comes in two forms, earplugs that are fitted into the ear canal and larger earmuffs that fit over and enclose the entire ear. These are generally used for different situations but can also be used together.

Ear PPE is available generally, often for occupational use (many industries involve noisy environments, from mining, motor-racing pit crews, to aviation and naval workers). For occupational use, a wider choice of PPE is available, partly due the need for wear over long periods (eg, 8-hour shifts), and for the tailored need to avoid over-protection (wearers may still need to hear warning sirens, on-site motor vehicles, etc.). Many of the more sophisticated custom-fit or active electronic PPE are not suitable or appropriate for use in an MR unit.

Most MR departments will routinely use disposable earplugs or earmuffs. Well-fitting ear plugs or muffs will typically offer noise attenuation of around 10–30 dB (varying across frequencies, see Fig. 3). This should generally bring acoustic noise exposure to within allowed limits. Earmuffs with hollow acoustic tubing are often supplied by the MR system vendor. These are generally not classified as ear protection but are a communication aid for staff instructing patients during scanning. These should not be used in place of equipment classified as ear protection. When used, good practice would be to combine them with earplugs. Due to their placement, earplugs tend to have more variable protection due to fit. If well maintained, earmuffs tend to offer more consistent protection.

Care should always be taken to ensure the device is in good condition and well-fitting. Take note of the attenuation data provided with the device and ensure it will provide sufficient noise reduction across the entire hearing range. A range

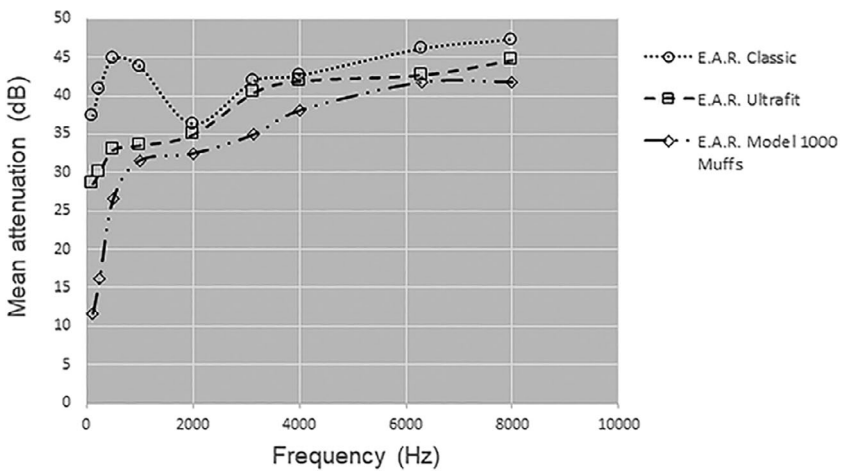

FIGURE 3: Noise attenuation for several commercial earplugs and ear defenders. Note the significant variability in attenuation at low frequencies. Reproduced by permission, the 3M Company. 3M™, E.A.R.™, and Peltor™ are trademarks of the 3M Company.

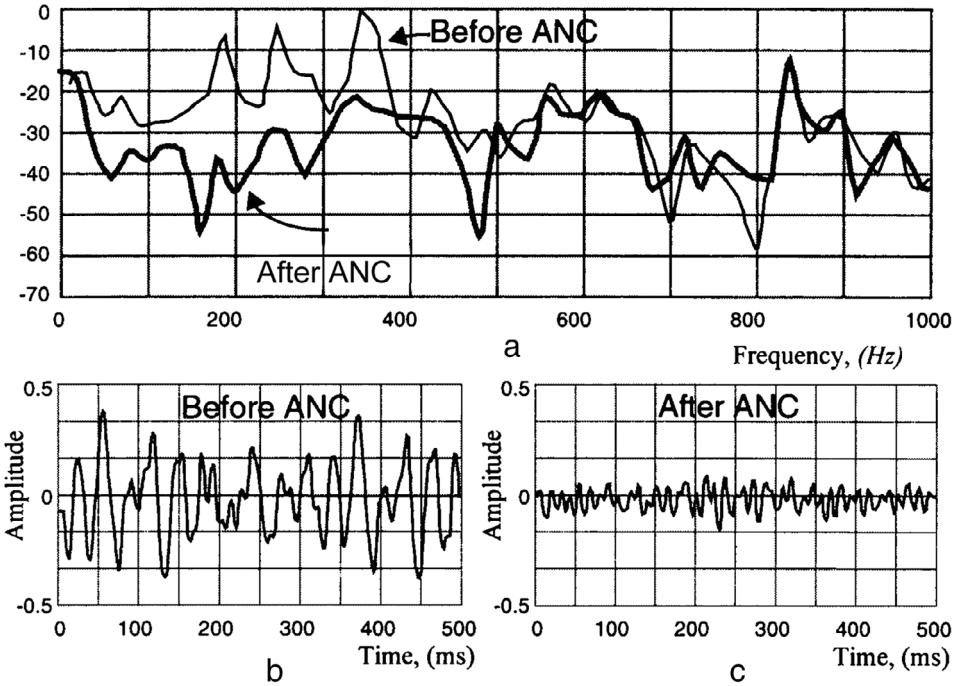

FIGURE 4: Results of noise cancelation for a typical clinical spin echo pulse sequence. Noise level spectra before (dotted line) and after cancelation (solid line) are shown for time and frequency domain spectra. A major disadvantage of this technique is that, if performed below optimal efficiency, at certain frequencies or in some spatial regions, noise levels may be enhanced rather than attenuated by the superposition of the additional antinoise.[50]

of devices may need to be available to cover the size of ear canal for subjects across the age range. Bear in mind, that in some circumstances, dual protection may be required (eg, neonatal imaging, see above), and some patients may express a preference. Current guidance suggests staff are trained in selection and fitting of ear-protection.[29]

Be aware that passive devices will offer nonuniform protection over the hearing range, with poorer noise attenuation at lower frequencies and poor attenuation of noise transmitted through bone conduction.[49]

Active Noise Control

Many will be familiar with the current trend for noise-canceling headphones to boost the enjoyment of listening to music in noisy environments such as those encountered when traveling. Essentially, acoustic noise at the ear is monitored with a microphone close to the music delivery speaker, and on-the-fly processing analyses background acoustic noise, and produces antiphase noise, which is delivered to the ear along with the music. The systems tend to work best for periodic background noise, rather than random or impulsive noise.

Using antiphase acoustic noise is not a new idea, but it is one which not only offers significant noise reduction but does so independently, that is, without modifying or degrading the performance of the MR system gradients or pulse sequences at all. Effective acoustic noise cancelation requires large amounts of fast processing, but advances in digital signal processing technology have made even these requirements relatively cheap and widely available on the high street.

Early studies showed encouraging results (see Fig. 4), with real-time peak noise reduction levels of 30 dB (over 0–700 Hz).[50] More recently, using a feed-forward x-LMS-based system, improved results have been reported, with attenuation levels of approximately 55 dB (with an average of 30 dBA across the entire hearing range.[51, 52]

Although speakers and mics can be built into the magnet inner bore, these active noise control systems work best, when the monitoring is performed at or very close to the ear, that is, in headphones. This leads to an obvious limitation of the system, as headphone use is not always possible with head coils, and standard equipment does not fit all patient groups. These issues have led to comparatively low interest and uptake for these systems in commercial MR systems to date.

Quiet MR Sequences

This approach initially seems unattractive, given the vast number of individual sequences on modern commercial scanners. Indeed, this fact partly explains why only a small set of acoustic noise-optimized sequences are generally offered on commercial scanners. However, it is also true that the majority of MR sequences are not excessively noisy and may not need additional optimization. Sequences with concerning levels of acoustic noise output are limited mainly to those acquiring data with multiple, rapid slew-rate, and high amplitude gradient levels (e.g., sequences such as EPI for fMRI,

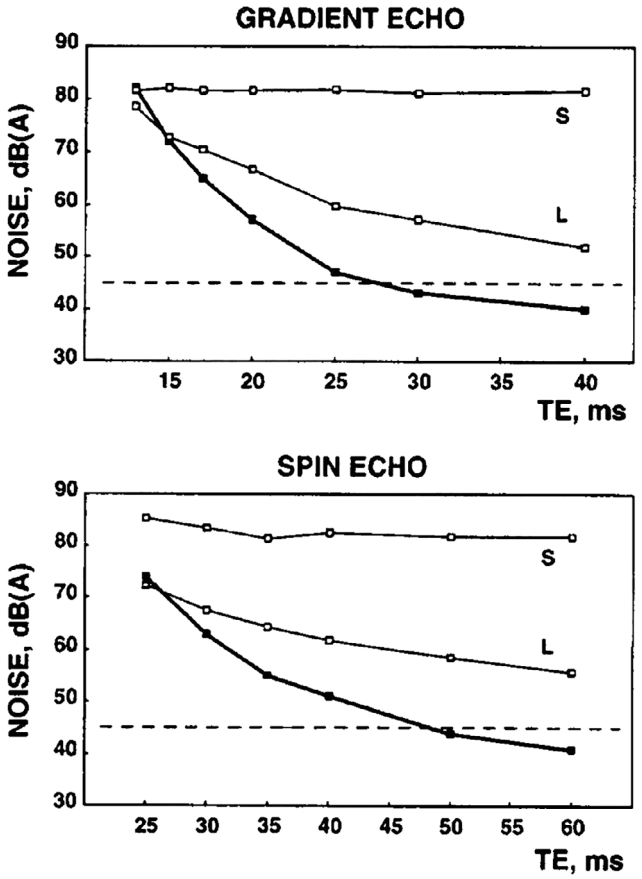

FIGURE 5: Acoustic noise levels for gradient-echo and spin-echo pulse sequences measured as a function of echo time (TE, milliseconds) at 3T. The top lines in the graphs correspond to sequences using soft (S) gradient pulses. The middle lines in the graphs show sequences with linear (L) ramps of maximum duration. The bottom lines in the graphs show standard sequence default settings. The dashed line is the level of ambient room noise from the air-conditioning system.[57] Reproduced by permission, Wiley - John Wiley & Son Publishers, NY.

diffusion, and fast 3D applications). In recent years, advances in this approach have generated almost silent imaging sequences, making it the solution of choice for several commercial vendors.

There are many approaches that can be used to optimize MR sequences to attenuate acoustic noise. Some of the main approaches that have been used alone, or in combination, are discussed below.

BASIC OPTIMIZATION FOR STANDARD SEQUENCES (INC. PARALLEL IMAGING). An understanding of the characteristics of MR-related acoustic noise, and scanner design (see above), allow us to make some choices, to reduce the acoustic noise associated with standard imaging.

As a first step, if possible choosing a spin-echo (SE) rather than a gradient-echo (GE) sequence will help.

Next, reduce the level of gradient activity: If possible, change from 3-D to 2-D acquisition and keep gradient amplitudes as low as possible. Reducing the gradient rise-time will also help, but will also increase TE, and affect the max slices, which can be acquired and overall exam time.[53] Reducing the number of gradient echoes will also help—replace gradient echoes with stimulated echoes, by using techniques such as STEAM Burst.[54, 55]

Parallel imaging such as SENSE can also be used to reduce gradient slew-rates due to reduced k-space sampling.[56] Acoustic noise attenuation levels of 10–15 dB are typical.

RESHAPING AND RESAMPLING. Acoustic noise is often associated with rapid and abrupt changes in gradient levels. Alongside reducing amplitudes and slew-rates, smoothing the gradient waveform will help, as it reduces the instances of sharp changes in gradient levels. It often features in sequence

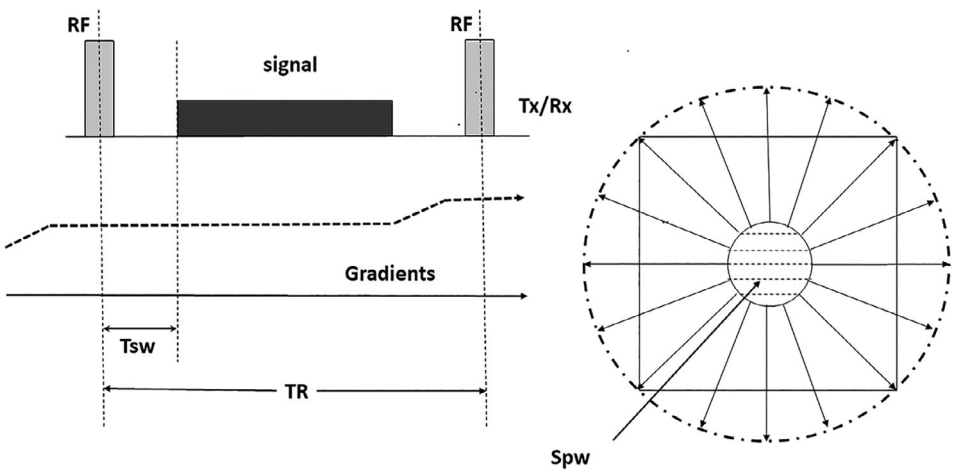

FIGURE 6: (left) Pulse sequence diagram for one repetition of the radial part of the PETRA sequence. Gradients are held constant during almost an entire TR period and altered only slightly at the end of each repetition without being ramped down. This very low gradient activity leads to minimal acoustic noise. T_{sw} is the time required to switch from transmission mode to receive mode. Redrawn from reference 81.

optimization. This solution involves the replacing trapezoidal waveforms with sinusoidal ones, maximizing gradient ramp duration and minimizing the number of ramps. These adaptions are sometimes referred to as using "soft" gradient pulses.[57] Early results were impressive (up to 45 dBA attenuation, see Fig. 5), but the sequences have increased vascular flow sensitivity, and results were poor with fast sequences. Later, this solution was also been applied to fast sequences,[58] generating 20–40 dBA acoustic noise attenuation. It continues to be popular.[59–65]

USING GRADIENT CANCELLATION PULSES. By adding some additional gradient pulses to the end of a sequence, it should be possible to cancel some of the Lorentz forces generated by gradient pulses earlier in the sequence—a solution similar to the use of antinoise approach (mentioned in the section Hearing and Acoustic Noise), but here using antiphase gradients, not antiphase noise, and so perhaps closer to the source of the problem, as it were. In practice, follow-on gradient pulses would generally aim to reduce the impact of a small set of dominant gradient modes and some of their harmonics. Initial results based on canceling three gradients modes, resulted in modest acoustic noise attenuation of 13 dB.[66]

MINIMIZING THE SCANNER RESPONSE FUNCTION. There is a similarity between the input function (gradient pulse spectrum) and output produced (acoustic noise spectrum) for an MR system. Knowing this, it is possible to generate a frequency response function (FRF) for an MR system, which will be independent of input and which will then allow us to predict the system response to any input function.[24]

Tomasi and Ernest [67] investigated the impact on the FRF of varying the switching frequency of the readout gradient (and bandwidth) for an EPI sequence. A frequency shift of 200 Hz resulted in acoustic noise reduction of 12 dB. This has also been used successfully by several other groups.[62, 63, 68, 69]

ULTRASHORT AND ZERO TE METHODS. To image tissue with short T2 values, ultra-short TE (UTE), and zero TE (ZTE) techniques have been developed.[70, 71] These techniques which are by their nature of short duration, use radial sampling of k-space and as the TRs are short, gradients can be left on rather than switching off between excitations. A bonus of these sequences is they result in almost silent imaging procedures, with acoustic noise levels similar to ambient room noise.

These sequences have been sufficiently successful, to provoke considerable interest from commercial MRI vendors. GE quickly implemented a variant of the UTE method (based on the RUFIS sequence[72]) as the basis for their Silenz/Silent Scan™ acoustic noise solution. Results from a protype running on a 3T MR system, produced acoustic noise levels of ~67 dB.[73] Others have reported on success with T2-w, T1-w, and diffusion UTE variants.[74–79]

The UTE/ZTE sequences inherently sample signal from FIDs rather than echoes. Hence, they are less sensitive to motion; however, long readout times can lead to image blurring. Some report of comparisons between UTE and non-UTE imaging for applications, such as MRA, has highlighted poor results for the UTE images.[80]

A further variant of these methods, uses pointwise-encoding time reduction with radial acquisition, so-called pointwise-encoding time reduction with radial acquisition (see Figure 6). This forms the kernel of Siemens Quiet Suite™ acoustic noise solution. Again, reports show very successful acoustic noise reductions.[81, 82]

The solution is also used by Philips, as part of their ComforTone™ system. Technical details are not available in the literature, but comparative assessments have been made with conventional sequences.[83] On a 1.5 T scanner running ComforTone™, acoustic noise attenuation levels were 10–20 dBA for a centre frequency 2–4 kHz. High-frequency attenuation was significantly better than at low frequencies, and in regions of the spectrum at low frequencies, there was slight enhancement of acoustic noise levels. The acoustic noise control also results in slight decreases in image quality.

Quiet Gradients

Acoustic noise in MR systems is an entirely unnecessary and unwanted side effect of equipment use. From an engineering perspective, the ideal solution for acoustic noise control, is to redesign equipment such that they do not generate unwanted acoustic noise. If suitable gradient systems were currently available, the practicalities of this solution for MR systems currently in use would mean either a potentially expensive upgrade to a new gradient set or some form of retrofit to optimize the existing gradient system. Neither solution compares well financially to solutions such as using effective disposable earplugs. However, the potential elegance and effectiveness across all sequences and all potential patients has kept research on-going in this area, toward this "grail-like" solution.

PASSIVE METHODS (RETROFITS). Insulation, evacuating, and perforation have been used to attenuate acoustic noise generated by Lorentz forces and the associated vibration and reverberation. Changes can be made to the gradient former material to increase the stiffness (i.e., Young's modulus), which will reduce acoustic noise. Lin et al[84] have reported reductions in the low-frequency range, and a reduction in resonance modes generated in the low-to-medium frequency range.

Many commercial MR systems use some form of material to absorb or dampen acoustic vibration. These generally have modest impact on acoustic noise, with attenuation levels

~3 dBA.[20,85] Better results were reported by Mechefske et al,[86] who combined damping with use of a scanner bore "endcap." They measured ~20 dB attenuation when running EPI on a 4T system. Unfortunately, dampening usually reduced gradient former stiffness.

Isolating the gradient system from the rest of the MR structure helps to stop acoustic noise transmission. Edelstein et al[87] reported levels of attenuation ~20 dB (peak) when using a sealed and evacuated gradient system. Later results from Katsunuma et al.[88] increased attenuation to ~30 dB. Toshiba use this approach, combined with insulation, and optimized "mute" sequences in their Pianissimo™ acoustic noise solution.[89] However, there is a dearth of data on its performance in the scientific literature to date. These often expensive approaches do not generally work well as retrofits.

An important aspect of research in this area is modeling. Much work has been done to assess the modal characteristics of gradient coil distortion, flexing, and vibration.[19, 90] Recently, further work has been done to develop and refine a comprehensive baseline analytical model (for a shielded cylindrical gradient coil) and to predict gradient coil behavior.[91] Their linear elastodynamic model shows, for example, that the same vibrational modes will be excited, irrespective of the spatial distribution of the coil windings, and that the width of resonances are decreased when there are shielding currents present.

ACTIVE METHODS (REDESIGNED COILS). One approach is similar to the antinoise technique noted above (see section Hearing and Acoustic Noise). It should be possible to design gradients where Lorentz forces produced by the image acquisition are balanced by other equal and opposite forces—the so-called force-balanced designs. Results from a prototype head-coil gradient set, running an EPI sequence on a 3T system, reported acoustic noise levels of 102 dB.[92, 93]

Summary

MRI procedures generate considerable acoustic noise, hindering communication with patients, and at high levels, impacting the success rate for scans and posing safety risks. Management of the risks from acoustic noise exposure involves providing protection for patients and staff to bring acoustic noise exposures within safe limits. Research on "hidden hearing loss"[13-15] may have an impact on the safe levels of acoustic noise exposure used in future for MR imaging.

Much research has been done to characterize the acoustic noise, and devise solutions to attenuate the noise and minimize associated risks.

Affordable passive ear protection, if good quality and good fit, is often sufficient to bring acoustic noise levels within safe levels. This can be doubled (wearing ear plugs and muffs) for sensitive patients to maximize acoustic noise attenuation, and specialized products are available with different fittings and sizes for pediatric patients.

Current documents regarding permissible limits vary, but in general set permissible average acoustic noise levels (at the patients' ear) of 85 dBA.[30, 33, 37] Acoustic noise levels outside the MR system's bore are lower and present reduced risks for an MRI healthcare worker present during the MRI examination.

There are a large variety of more complex approaches, involving the use of antinoise and antivibration methods, sequence optimization to reduce gradient activity, and redesigned gradient hardware.

Of the available solutions, comparatively recent UTE and ZTE methods ([70–82]) have generated MR sequences which are virtually silent, producing acoustic noise levels similar to ambient room values. The current "silent" scanning techniques have also been proven to improve pediatric scan success rates.[94] These solutions are available for a small range of sequences on most modern commercial scanners.

References

1. Brummett RE, Talbot JM, Charuhas P. Potential hearing loss resulting from MR imaging. Radiology 1988;169:539-540.
2. Quirk ME, Letendre AJ, Ciottone RA, Lingley JF. Anxiety in patients undergoing MR imaging. Radiology 1989;170:463-466.
3. Laurell G. The combined effect of noise and cisplatin. Ann Otol Rhinol Laryngol 1992;1001:969-976.
4. Philbin MK, Taber KH, Hayman LA. Preliminary report: Changes in vital signs of term newborns during MR. Am J Neurorad 1996;17:1033-1036.
5. Kanal E, Shellock FG, Talagala L. Safety considerations in MR imaging. Radiology 1990;176:593-606.
6. Shellock FG, Kanal E. Policies, guidelines, and recommendations for MR imaging safety and patient management. J Magn Reson Imaging 1991;1:97-101.
7. Shellock FG, Litwer CA, Kanal E. Magnetic resonance imaging: bioeffects, safety, and patient management. Magn Reson Q 1992;4:21-63.
8. Kanal E, Shellock FG, Sonnenblick D. MRI clinical site safety survey: Phase I results and preliminary data. Magn Reson Imaging 1988;7:106-112.
9. De Wilde JP, Grainger D, Price DL, Renaud C. Magnetic resonance imaging safety issues including an analysis of recorded incidents within the UK. Prog Nucl Magn Reson Spectr 2007;51:37-48.
10. McJury M, Shellock F. Auditory noise associated with MRI procedures: A review. J Mag Res Imaging 2000;12:37-45.
11. McJury M. Acoustic noise associated with MRI. In: Shellock F, Crues J, editors. *MRI bioeffects, safety and patient management*: Biomedical Publishing Group In press.
12. Department of Health. *Acoustics: Design considerations, HTM 2045*. London: HMSO; 1996.
13. Liberman MC. Hidden hearing loss: Primary neural degeneration in the noise-damaged and aging cochlea. Acoust Sci Tech 2020;41:59-62.
14. Kohrman DC, Wan G, Cassinotti L, Corfas G. Hidden hearing loss: A disorder with multiple etiologies and mechanisms. Cold Spring Harb Perspect Med 2020;10:a035493.
15. Hickox AE, Larsen E, Heinz MG, Shinobu L, Whitton JP. Translational issues in cochlear synaptopathy. Hear Res 2017;349:164-171.

16. A variety of typical MRI-generated acoustic sounds. Accessed September 01, 2020. Available from: https://www.youtube.com/watch?v=6Aj2QspPf7s.

17. Price DL, De Wilde JP, Papadaki AM, Curran JS, Kitney RI. Investigation of acoustic noise on 15 MRI scanners from 0.2 to 3 T. J Magn Reson Imaging 2001;13:288-293.

18. Moelker A, Wielopolski PA, Pattynama PMT. Relationship between magnetic field strength and magnetic resonance-related acoustic noise. Magn Reson Mater Phys Biol 2003;16:52-55.

19. Winkler SA, Schmitt F, Landes H, et al. Gradient and shim technologies for ultra high field MRI. Neuroimage 2018;168:59-70.

20. Counter SA, Olofsson A, Grahn HF, Borg E. MRI acoustic noise: Sound pressure and frequency analysis. J Magn Reson Imaging 1997;7:606-611.

21. Prasher D. *Estimation of hearing damage from noise exposure. Report from the technical meeting on exposure-response relationships of noise on health, Bonn, Germany*. Geneva: World Health Organisation; 2003. p 82-97.

22. Schmitter S. Entwicklung von geräuscharmen Bildgebungstechniken für die funktionelle Magnetresonanztomographie. Doctoral thesis, 2008.

23. More SR, Lim TC, Li M, Holland CK, Boyce SE, Lee JH. Acoustic noise characteristics of a 4T MRI scanner. J Magn Reson Imaging 2006;23:388-397.

24. Hedeen RA, Edelstein WA. Characteristics and prediction of gradient acoustic noise in MR imagers. Magn Reson Med 1997;37:7-10.

25. Capstick M, McRobbie D, Hand J, Christ A, Kühn S, Mild KH, et al. An investigation into occupational exposure to electromagnetic fields for personnel working with and around medical magnetic resonance imaging equipment. 2008. Project Report VT/2007/017. Accessed September 25, 2019. Available from: https://itis.swiss/news-events/news/publications/2008/an-investigation-into-occupational-exposure-to-electromagnetic-fields-for-personnel-working-with-and-around-medical-magnetic-resonance-imaging-equipment/ .

26. Schmitter S, Mueller M, Semmler W, Bock M. Maximum sound pressure levels at 7 Tesla—what's all this fuss about? Proc ISMRM 2014;3029.

27. Ravicz ME, Melcher JR, Kiang NYS. Acoustic noise during functional MRI. J Acoust Soc Am 2000;108:1683-1696.

28. Foster JR, Hall DA, Summerfield AQ, Palmer AR, Bowtell RW. Sound level measurements and calculations of safe noise dosage during EPI at 3 T. J Magn Reson Imaging 2000;12:157-163.

29. Medicines and Healthcare Products Regulatory Authority (MHRA). Safety guidelines for magnetic resonance imaging equipment in clinical use, 2015.

30. *Control of noise at work*. London: HMSO; 2005.

31. International Electrotechnical Commission (IEC). Particular requirements for the safety of magnetic resonance equipment for medical diagnosis. Geneva: IEC;60601-2-33; 2001.

32. International Commission on Non-Ionizing Radiation (ICNIRP). Guidelines on limits of static magnetic fields. Health Phys 1994;66:100-106.

33. International Commission on Non-Ionizing Radiation (ICNIRP). Statement on MR procedures: Protection of patients. Health Phys 2004;87:197-216.

34. Occupational Safety and Health Administration (OSHA). Occupational noise exposure. 29 C.F.R. 1988;1910.95.

35. Kanal E, Barkovich AJ, Bell C, et al. ACR guidance document on MR safe practices: 2013. J Mang Reson Imaging 2013;37:501-530.

36. U.S. Food and Drug Administration. *Criteria for significant risk investigations of magnetic resonance diagnostic devices. Guidance for industry and food and drug administration staff*. Rockville, MD: Food and Drug Administration Center for Devices and Radiological Health; 2014.

37. Etzel RA, Balk SJ, Bearer CF, Miller MD, Shea KM, Simon PR. Noise: A hazard for the fetus and newborn. Paediatrics 1997;100:724-727.

38. Glover P, Hykin J, Gowland P, Wright J, Johnson J, Mansfield PM. An assessment of the intrauterine sound intensity level during obstetric echo-planar magnetic resonance imaging. Brit J Rad 1995;68:1090-1094.

39. Gélat P, David AL, Haqhenas SR, et al. Evaluation of fetal exposure to external loud noise using a sheep model: Quantification of in utero acoustic transmission across the human audio range. Am J Obstet Gynecol 2019;221:343.e1-343.e11.

40. Gerhardt KJ, Abrams RM. Fetal exposures to soundand vibroacoustic stimulation. J Pernat 2000;20:S20-S29.

41. Reeves MJ, Brandreth M, Whitby EH, et al. Neonatal cochlear function: Measurement after exposure to acoustic noise during in utero MR imaging. Radiology 2010;257:802-809.

42. Bouyssi-Kobar M, du Plessis AJ, Robertson RL, Limperopoulos C. Fetal magnetic resonance imaging: Exposure times and functional outcomes at preschool age. Pediatr Radiol 2015;45:1823-1830.

43. De Vita E, Bainbridge A, Cheong JLY, et al. Magnetic resonance imaging of neonatal encephalopathy at 4.7 Tesla: Initial experiences. Pediatrics 2006;118:e1812-e1821.

44. Jaimes C, Delgado J, Cunnane MB, et al. Does 3-T fetal MRI induce adverse acoustic effects in the neonate? A preliminary study comparing postnatal auditory test performance of fetuses scanned at 1.5 and 3 T. Pediatr Radiol 2019;49:37-45.

45. Clements H, Duncan KR, Fielding K, Gowland PA, Johnson IR, Baker PN. Infants exposed to MRI in utero have a normal paediatric assessment at 9 months of age. Brit J Radiol 2000;73:190-194.

46. White RD, Smith JA, Shepley MM. Recommended standards for newborn ICU design. J Perinatol 2013;33:S2-S16.

47. Tkach JA, Merhar SL, Kline-Fath BM, et al. MRI in the neonatal ICU: Initial experience using a small-footprint 1.5-T system. Am J Radiol 2013;202:W95-W105.

48. Tzach JA, Li Y, Pratt RG, et al. Characterization of acoustic noise in a neonatal intensive care unit MRI system. Pediatr Radiol 2014;44:1011-1019.

49. Naughton RF. The measurement of hearing by bone conduction. In: Jerger J, editor. *Modern developments in audiology*. New York, NY: Academic Press; 1963.

50. McJury M, Stewart RW, Crawford D, Toma E. The use of active noise control (ANC) to reduce acoustic noise generated during MRI scanning: Some initial results. Mag Res Imaging 1997;15:319-322.

51. Li M, Rudd B, Lim TC, Lee JH. In situ active control of noise in a 4T MRI scanner. J Magn Reson Imaging 2011;34:662-669.

52. Lee N, Park Y, Lee GW. Frequency-domain active noise control for magnetic resonance imaging acoustic noise. Appl Acoust 2017;118:30-38.

53. Skare S, Nordell B, et al. An incubator and "quiet" pulse sequences for MRI examination of premature neonates. Proc ISMRM 1996;1727.

54. Jakob P, Schlaug MG, Griswold M, et al. Functional burst imaging. Magn Reson Med 1998;40:614-621.

55. Cremillieux Y, Wheeler-Kingshott CA, Briguet A, Doran SJ. STEAM-BURST: A single-shot multi-slice imaging sequence without rapid gradient switching. Mag Res Med 1997;38:645-652.

56. de Zwart JA, Van Gelderen P, Kellman P, Duyn JH. Reduction of gradient acoustic noise in MRI using SENSE-EPI. Neuroimage 2001;16:1151-1155.

57. Hennel F, Giard F, Loenneker T. Silent MRI with soft gradient pulses. Mag Res Med 1999;42:6-10.

58. Hennel F. Fast spin echo and fast gradient echo MRI with low acoustic noise. J Magn Reson Imaging 2001;13:960-966.

59. Loenneker T, Hennel F, Ludwig U, Hennig J. Silent BOLD imaging. Magn Reson Mater Phys Biol Med 2001;13:76-81.

60. Osterle C, Hennel F, Hennig J. Quiet imaging with interleaved spiral read-out. Magn Reson Imaging 2001;19:1333-1337.

61. Schmitter S, Diesch E, Amann M, Kroll A, Moayer M, Schad LR. Silent echo-planar imaging for auditory FMRI. Magn Reson Mater Phys 2008; 21:317-325.

62. Schmitter S, Bock M. Acoustic noise-optimized VERSE pulses. Magn Reson Med 2010;64:1447-1453.

63. Zapp J, Schmitter S, Schad LR. Sinusoidal echo-planar imaging with parallel acquisition technique for reduced acoustic noise in auditory fMRI. J Magn Reson Imaging 2012;36:581-588.

64. Heismann B, Ott M, Grodzki D. Sequence-based acoustic noise reduction of clinical MRI scans. Magn Reson Med 2015;73:1104-1109.

65. Fischer S, Grodzki DM, Domschke M, Albrecht M, Bodelle B, Eichler K. Quiet MR sequences in clinical routine: Initial experience in abdominal imaging. Radiol Med 2017;122:194-203.

66. Shou X, Chen X, Derakhshan J, et al. The suppression of selected acoustic frequencies in MRI. Appl Acoust 2010;71:191-200.

67. Tomasi DG, Ernst T. Echo planar imaging at 4 Tesla with minimum acoustic noise. J Magn Reson Imaging 2003;18:128-130.

68. Segbers M, Rizzo-Sierra CV, Duifhuis H, Hoogduin JM. Shaping and timing gradient pulses to reduce MRI acoustic noise. Magn Reson Med 2010;64:546-553.

69. Ott M, Blaimer M, Grodzki DM, et al. Acoustic-noise-optimized diffusion-weighted imaging. Magn Reson Mater Phy 2015;28:511-521.

70. Gatehouse PD, Bydder GM. Magnetic resonance imaging of short T_2 components in tissue. Clin Radiol 2003;58:1-19.

71. Weiger M, Brunner DO, Dietrich BE, Meuller CF, Pruessmann KP. ZTE Imaging in Humans. Magn Reson Med 2013;70:328-332.

72. Madio DP, Lowe IJ. Ultra-fast imaging using low flip angles and FIDs. Magn Reson Med 1995;34:525-529.

73. Alibek S, Vogel M, Sun W, et al. Acoustic noise reduction in MRI using silent scan: An initial experience. Diagn Interv Radiol 2014;20:360-363.

74. Ohlmann-Knafo S, Morlo M, Tarnoki DL, et al. Comparison of image quality characteristics on silent MRversusconventional MR imaging of brain lesions at 3 Tesla. Br J Radiol 2016;89:20150801.

75. Solana AB, Menini A, Sacolick LI, Hehn N, Wiesinger F. Quiet and distortion-free, whole brain BOLD fMRI using T2-prepared RUFIS. Magn Reson Med 2016;75:1402-1412.

76. Wiesinger F, Menini A, Solana AB. Looping star. Magn Reson Med 2019;81:57-68.

77. Yuan J, Hu Y, Menini A, et al. Near-silent distortionless DWI using magnetization-prepared RUFIS. Mag Res Med 2019;84:170-181.

78. Sandberg JK, Young VA, Syed AB, et al. Near-silent and distortion-free diffusion MRI in pediatric musculoskeletal disorders: Comparison with Echo planar imaging diffusion. J Magn Reson Imaging 2021;53:504-513. https://doi.org/10.1002/jmri.27330.

79. Liu X, Gómez PA, Solana AB, Wiesinger F, Menzel MI, Menze BH. Silent 3D MR sequence for quantitative and multicontrast T1 and proton density imaging. Phys Med Biol 2020;65:185010. https://doi.org/10.1088/1361-6560/aba5e8.

80. Holdsworth SJ, Macpherson SJ, Yeom KW, Wintermark M, Zaharchuk G. Clinical evaluation of silent T_1-weighted MRI and silent MR angiography of the brain. Am J Radiol 2018;210:404-411.

81. Ida M, Wakayama T, Nielsen ML, Abe T, Grodzki DM. Quiet T1-weighted imaging using PETRA: Initial clinical evaluation in intracranial tumor patients. J Magn Reson Imaging 2015;41:447-453.

82. Aida N, Niwa T, Fujii Y, et al. Quiet T_1-weighted pointwise encoding time reduction with radial acquisition for assessing myelination in the pediatric brain. Am J Neuroradiol 2016;37:1528-1534.

83. Yamashiroa T, Moritab K, Nakajimaa K. Evaluation of magnetic resonance imaging acoustic noise reduction technology by magnetic gradient waveform control. Mag Reson Imaging 2019;63:170-177.

84. Lin TR, O'Shea P, Mechefske CK. Reducing MRI gradient coil vibration with rib stiffeners. Concepts Magn Reson Part B 2009;35B:198-209.

85. Sellers MB, Pavlids JD, Carlberger T. MRI acoustic noise. Int J Neuroradiol 1996;2:549-560.

86. Mechefske CK, Geris R, Gati JS, Rutt BK. Acoustic noise reduction in a 4T MRI scanner. Magn Reson Mater Phys Med Biol 2002;13:172-176.

87. Edelstein WA, Hedeen RA, Mallozzi RP, El-Hamamsy SA, Ackermann RA, Havens TJ. Making MR quieter. Magn Reson Imaging 2002;20:155-161.

88. Katsunuma A, Takamori H, Sakakura Y, Hamamura Y, Ogo Y, Katayama R. Quiet MRI with novel acoustic noise reduction. Magn Reson Mater Phys Med Biol 2002;13:139-144.

89. Toshiba America Medical Systems Improved auditory fMRI imaging using Toshiba scanner with pianissimo. MRWP12219US. 2014.

90. Mechefske CK. Vibration in MRI scanners. In: Al-Jumaily A, Alizad A, editors. *Biomedical applications of vibration and acoustics in therapy, bioeffects, and modeling*. New York, NY: ASME Press; 2008.

91. Sakhr J, Chronik BA. Vibrational response of a MRI gradient coil cylinder to time-harmonic Lorentz-force excitations: An exact linear elastodynamic model for shielded longitudinal gradient coils. Appl Math Model 2019;74:350-372.

92. Mansfield P, Glover PM, Bowtell RW. Active acoustic screening: Design principles for quiet gradient coils in MRI. Meas Sci Technol 1994;5: 1021-1025.

93. Mansfield P, Chapman BL, Bowtell R, Glover P, Coxon R, Harvey PR. Active acoustic screening: Reduction of noise in gradient coils by Lorentz force balancing. Magn Reson Med 1995;33:276-281.

94. Zhu X, Ye J, Bao Z, et al. Benefits of silent DWI MRI in success rate, image quality, and the need for secondary sedation during brain imaging of children of 3–36 months of age. Acad Radiol 2020;27:543-549.